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Multiplicity among peculiar A stars I. The Ap stars HD 8441 and HD 137909, and the Am stars HD 43478 and HD 96391*,**

P. North[1], J.-M. Carquillat[2], N. Ginestet[2], F. Carrier[1], and S. Udry[3]

[1] Institut d'Astronomie de l'Université de Lausanne, CH-1290 Chavannes-des-bois, Switzerland
[2] Observatoire Midi Pyrénées, 14 avenue Edouard Belin, F-31400 Toulouse, France
[3] Observatoire de Genève, CH-1290 Sauverny, Switzerland

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Abstract. We present the first results of a radial-velocity survey of cool Ap and Am stars. HD 8441 is not only a double system with P = 106.357 days, but is a triple one, the third companion having an orbital period larger than 5000 days. Improved orbital elements are given for the classical Ap star HD 137909 = β CrB by combining our radial velocities with published ones. We yield new orbital elements of the two Am, SB2 binaries HD 43478 and HD 96391. Good estimates of the individual masses of the components of HD 43478 can be given thanks to the eclipses of this system, for which an approximate photometric solution is also proposed.

Key words: Stars: chemically peculiar – Stars: spectroscopic binaries – Stars: eclipsing binaries – Stars: fundamental parameters – Stars: individual: HD 8441, HD 43478, HD 93961, HD 137909

1. Introduction

Multiplicity plays an essential, though as yet poorly understood, role in the formation and maybe the evolution of A-type chemically peculiar stars. While the rate of binaries tends to be rather small among the magnetic Ap stars, with an especially strong deficit of SB2 binaries, it is very high among the Am stars, which on the contrary, are very often found in SB2 systems. There is also a conspicuous lack of orbital periods smaller than 3 days among the magnetic Ap stars, as shown e.g. in the review by Gerbaldi et al. (1985). The multiplicity of Am stars has been explored by Abt & Levy (1985), and their work showed that all Am stars are not necessarily found in binaries (contrary to what earlier results suggested), or at least not in short-period binaries (even though "short" means $P < 1000$ days). This indicates that duplicity is not an absolute prerequisite for the Am peculiarity to appear, so that the slow rotation of these stars, which presumably allows radiative diffusion to work in their atmosphere (Michaud et al. 1983), is not always due to tidal friction (Abt 1985, Abt & Levy 1985).

In order to increase the as yet insufficient statistics, a radial velocity survey of cool, magnetic Ap stars has been initiated in 1985 using the CORAVEL scanner. Some Am stars were also monitored in the course of this programme, for ambiguous classification caused them to be considered as Ap stars. Preliminary results of this survey have been published by North (1994). Observations of Am stars with CORAVEL had been initiated in the early eighties by M. Mayor and W. Benz, with the purpose of determining their projected rotational velocities, but the results were not published. Since this project was not intended to determine the rate of binaries, only few stars have more than 2 or 3 measurements, and HD 96391 was one of them.

In 1992, two of us (JMC and NG) began a radial-velocity survey of all northern Am stars whose metallic type is cooler than or equal to F2, with the purpose of improving our knowledge of their multiplicity. The limit imposed on the spectral type deduced from the metallic lines was chosen because of CORAVEL's optimum efficiency for cool stars. The stars HD 43478 and 96391 were included in this survey and were therefore measured independently by the Geneva-Lausanne observers as well as by the Toulouse observers. The latter measured also a few

Send offprint requests to: P. North

* Based on observations made at the Observatoire de Haute Provence (CNRS), France, at the Jungfraujoch station of Observatoire de Genève, Switzerland, and on data from the ESA Hipparcos satellite

** Tables 6 to 12 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Ap stars, and we present here the results based on the merged data of these common stars.

The observations are briefly described in Section 2 while the results are presented and discussed in Sections 3 and 4 for the Ap and Am stars respectively. Extensive use has been made of Renson's (1991) catalogue in this work.

2. Observations

The radial velocity observations were done at Observatoire de Haute-Provence with the CORAVEL scanner attached to the 1-meter Swiss telescope. Although this instrument is optimized for late-type stars, it can still yield very good results on slowly rotating F stars, and even on A stars if their metallic lines are enhanced, as is the case of Ap and Am stars. Some Ap and Am stars have been measured as early as 1980, but more systematic surveys began in 1985 and in 1992 for the Ap and Am stars respectively.

The photometric observations were made in the Geneva system at different observing sites (Observatoire de Haute-Provence, Gornergrat and Jungfraujoch), but most observations of HD 43478 were made at Jungfraujoch (Switzerland) with the 76-cm telescope.

The individual radial velocities of all stars, as well as individual photometric measurements of HD 43478, are listed in Tables 6 to 12.

3. Results on Ap stars

3.1. HD 8441 (= BD +42° 293 = Renson 2050)

This bright A2 Sr star was already known as an SB1 system. Its rotational period, known from its photometric variability, is 69.43 days (Rakosch & Fiedler 1978). Renson (1966) found an orbital period of 106.3 days and published the radial-velocity curve, but not the orbital parameters. A total of 107 measurements have been made over almost 5000 days (Table 6), which confirms the 106 days period (see Fig. 1). However, the residuals are larger than expected from the precision of the measurements, and follow a very clear trend (see Fig. 2). The presence of a third component is certain, although its period is so long that we could not cover even one cycle. The orbital parameters of the primary are given in Table 1. This is the second spectroscopic triple system known among Ap stars, after the SiMg star HD 201433 whose periods are much shorter (see the catalogue of Tokovinin 1997). The projected rotational velocity estimated from the width of the autocorrelation dip (Benz & Mayor 1984) is given in Table 2, with the restriction that in principle, such a quantity can only represent an upper limit to the true $v \sin i$. Indeed, the magnetic field commonly present among Ap Sr stars broadens the lines through the Zeeman effect, so that $v \sin i$ will be overestimated if this effect is neglected. In this particular case, however, the estimated $v \sin i$ is quite compatible with the 69.43 days rotational period, assuming a radius $R \sim 3\ R_{\odot}$.

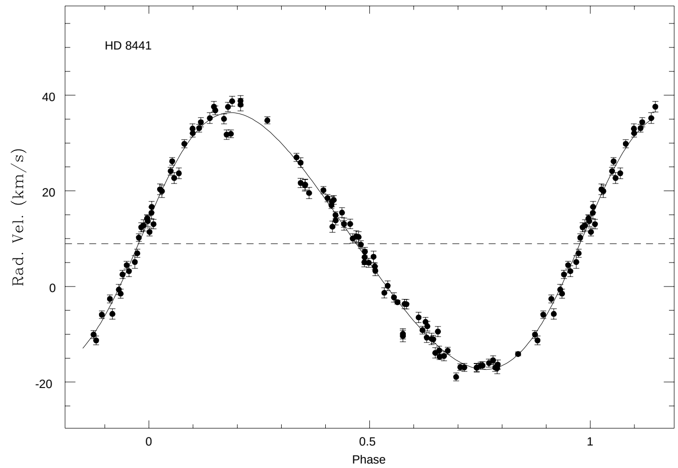

Fig. 1. Radial-velocity curve of HD 8441. The period is 106.357 ± 0.009 days.

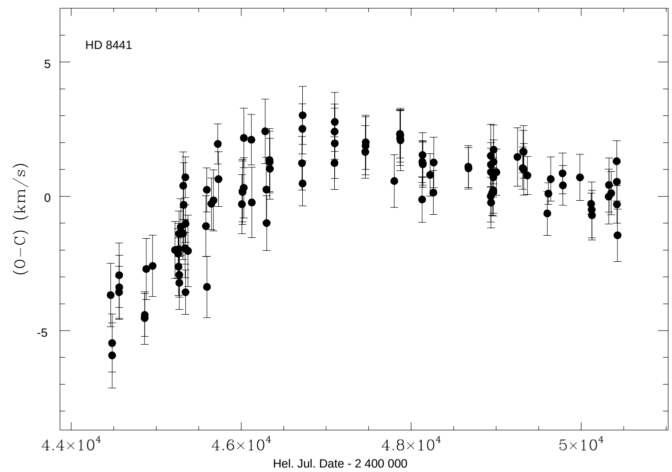

Fig. 2. Radial-velocity residuals vs time for HD 8441.

The Hipparcos parallax of this star is 4.91 ± 0.80 mas (Perryman et al. 1997); this translates into a distance $d = 232$ pc, after having applied a Lutz-Kelker correction (Lutz & Kelker 1973) $\Delta M = -0.28$ which takes into account the exponential decrease of stellar density in the direction perpendicular to the galactic plane. On the other hand, the visual absorption estimated from Geneva photometry is $A_v = 0.13$. Assuming a contribution of about 0.23 magnitudes of the companions to the visual magnitude of the system, the apparent magnitude of the primary alone is $V = 6.92$, and finally we obtain an absolute magnitude $M_V = -0.03 \pm 0.42$ for this component. Adopting $T_{\rm eff} = 9200$ K (Adelman et al. 1995) and interpolating in the evolutionary tracks of Schaller et al. (1992) for a solar metallicity $Z = 0.018$[1] (and for a mod-

[1] This choice of a solar metallicity may appear surprising at first sight for Ap and Am stars, whose atmospheric com-

Table 1. Orbital parameters of the binaries. For each component, the second line gives the estimated standard deviations of the parameters

Star name	P (days)	$T_\circ$ (HJD -2400000)	e	$V_\circ$ ($\mathrm{km\,s^{-1}}$)	ω_1 ($^\circ$)	$K_{1,2}$ ($\mathrm{km\,s^{-1}}$)	$\mathcal{M}_{1,2}\sin^3 i$ $f_1(\mathcal{M})$	$a_{1,2}\sin i$ 10^6 km	N	(O−C) $\mathrm{km\,s^{-1}}$
HD 8441	106.357	44952.21	0.122	8.94	279.76	26.85	0.209	38.98	107	1.86
	0.009	1.32	0.010	0.19	4.75	0.29	0.007	0.42		
HD 43478	5.464086	47000.1758	0	-6.63	0	86.48	1.777	6.498	56	1.95
	0.000011	0.0037	fixed	0.18	fixed	0.34	0.015	0.025		
					180	95.03	1.617	7.14	57	
					fixed	0.35	0.014	0.03		
HD 96391	4.915427	45234.2422	0	-1.67	0	84.69	1.408	5.724	44	1.70
	0.000008	0.0061	fixed	0.20	fixed	0.37	0.015	0.025		
					180	90.19	1.322	6.10	36	
					fixed	0.46	0.014	0.03		
HD 137909	3831.50	44421.40	0.5430	-21.48	180.56	9.45	0.1987	417.98	78	0.45
	7.94	7.63	0.0069	0.06	1.05	0.09	0.0063	4.52		
Whole sample	3858.13	25119.6	0.5219	-21.81	180.37	9.21	0.1943	416.81	316	0.93
	2.96	17.1	0.0064	0.06	1.15	0.08	0.0058	4.13		
P fixed	3858.13	40545.39	0.5340	-21.49	180.87	9.31	0.1955	417.66	78	0.47
	fixed	7.45	0.0067	0.06	1.14	0.07	0.0056	3.96		

Table 2. Visual magnitude and $v\sin i$ of the programme stars.

Star name	V	v sin$i$ A ($\mathrm{km\,s^{-1}}$)	v sin$i$ B ($\mathrm{km\,s^{-1}}$)
HD 8441	6.691	$\leq 2.35 \pm 0.60$	
HD 137909	3.670	$\leq 7.72 \pm 0.15$	
HD 43478	7.483	28.11 ± 2.81	20.61 ± 2.06
HD 96391	7.08	23.54 ± 2.35	18.04 ± 0.67

erate overshooting distance $d_{over}/H_p = 0.2$), one obtains $\mathcal{M}_1 = 2.76 \pm 0.18 \mathcal{M}_\odot$, $\log g = 3.71 \pm 0.12$ (g in *cgs* units) and $R = 3.86 \pm 0.66\, R_\odot$. Although the uncertainties are fairly large, the primary is evolved and on the verge of leaving the Main Sequence; it is satisfying that our small $\log g$ value agrees with the spectroscopic estimate of Adelman et al. (1995) who gave $\log g = 3.35 - 3.8$.

position is precisely far from solar. However, it is generally admitted that chemical peculiarities are confined to the superficial layers of the star (through radiative diffusion) so that the metal content integrated over the whole stellar mass is the same as for normal stars, and the deep internal structure remains roughly normal. But it is true that standard evolutionary tracks should be considered as a first approximation only for Ap and Am stars; they are also the only ones available as yet, though Michaud & Richer (1997) have recently computed fully consistent evolutionary tracks for F stars, including the effect of radiative diffusion on the internal stellar structure.

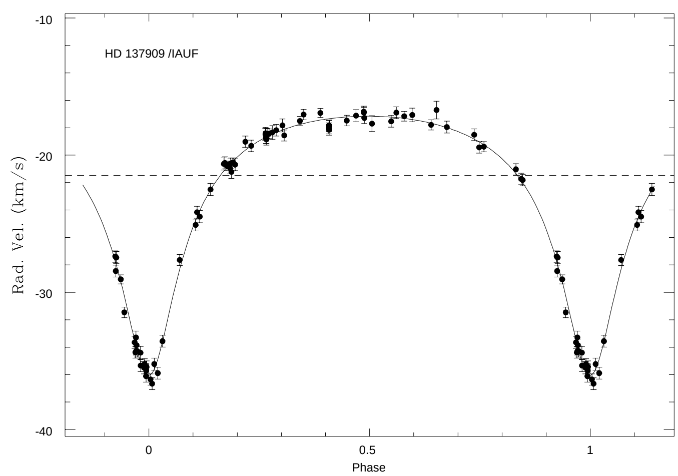

Fig. 3. Radial-velocity curve of HD 137909 given by CORAVEL only. The period is 3831.50 ± 7.94 days.

3.2. β CrB (= HD 137909 = BD +29° 2670 = Renson 39200)

This is a well-known, prototype cool Ap star classified A9 SrEuCr. Its rotational period, known from photometric, spectroscopic and magnetic variations is 18.4868 days (Leroy 1995). It is known as a binary, by both spectroscopy and speckle interferometry. A radial-velocity curve was published by Kamper et al. (1990) together with an as-

trometric orbit based on speckle observations. These authors suspected that a third body might be present, on the basis of radial velocities taken at Lick Observatory between 1930 and 1943. The system was monitored with CORAVEL for a little more than one cycle, which is very long, and 78 measurements have been obtained (see Table 7). The V_r curve is shown in Fig. 3 and the spectroscopic orbit is given in Table 1. Thanks to the precision and the homogeneity of the data, our V_r curve is more precise than that based on the data taken at David Dunlap Observatory by Kamper et al. Combining our measurements with those published by Kamper et al. (1990), by Oetken & Orwert (1984) and by Neubauer (1944), we can refine the period to $P = 3858.13$ days, but the accuracy of the orbital elements is not improved, due to the scatter of the residuals, which is more than twice larger than for CORAVEL observations alone. In order to fit Neubauer's data to the others, we had to subtract a constant value ($2\ \mathrm{km\,s^{-1}}$) to them, which was also done by Kamper et al. (1990). The resulting radial-velocity curve is shown in Fig. 4 and the corresponding orbital elements are given in Table 1. The residuals are shown in Figure 5. A fit of the CORAVEL radial velocities alone has also been done keeping the orbital period fixed to the above, refined value and its results are displayed in the last line of Table 1. The scatter of the $O-C$ residuals is hardly increased and only the eccentricity and the amplitude change by more than one sigma with respect to the fit where P was adjusted; the change is probably due to the rather inhomogeneous phase coverage of the observations.

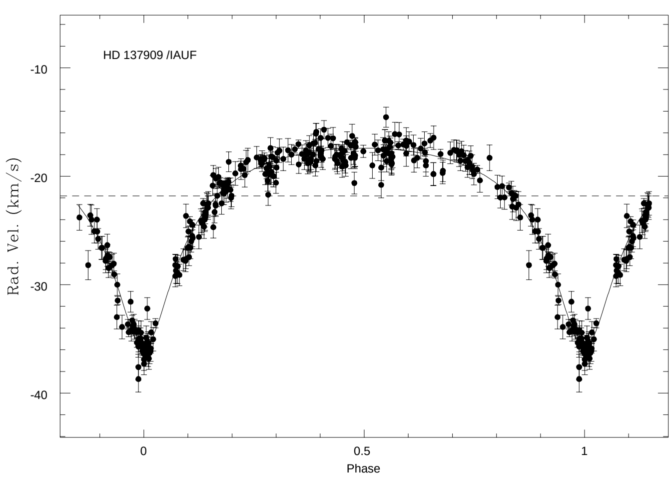

Fig. 4. Radial-velocity curve of HD 137909 including data published by Kamper et al. (1990), by Neubauer (1944) and by Oetken & Orwert (1984). A correction of $-2\,\mathrm{km\,s^{-1}}$ has been added to the V_r values of Neubauer. The period is 3858.13 ± 2.96 days.

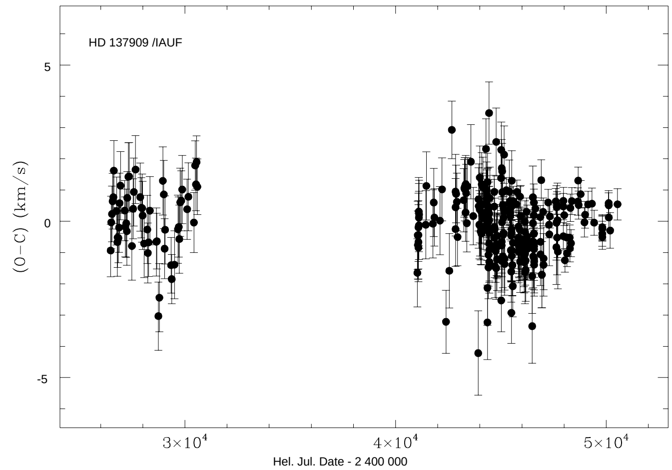

Fig. 5. Radial-velocity residuals vs time for HD 137909 for the whole sample.

Thanks to the Hipparcos satellite, β CrB has now a very precise parallax $\pi = 28.60 \pm 0.69$ mas which allows to compute the linear semi-major axis of the relative orbit from the angular semi-major axis obtained by speckle interferometry (203.2 ± 1.4 mas). Since the inclination angle $i = 111.11^\circ \pm 0.46^\circ$ of the orbit is known from speckle interferometry and the quantity $a_1 sin\ i$ is known from CORAVEL measurements, the semi-major axis of the absolute orbit of the companion can be computed:

$$a_2 = a - a_1 = 4.114 \pm 0.031\ U.A. = 615.2 \times 10^6 km \quad (1)$$

as well as the mass ratio :

$$\frac{\mathcal{M}_2}{\mathcal{M}_1} = \frac{a_1}{a_2} = 0.727 \pm 0.033 \quad (2)$$

Finally, one can obtain $\mathcal{M}_2 = 1.356 \pm 0.073\ \mathcal{M}_\odot$ from the mass function, as well as $\mathcal{M}_1 = 1.87 \pm 0.13\ \mathcal{M}_\odot$. Oetken & Orwert (1984) had found $\mathcal{M}_1 = 1.82$ and $\mathcal{M}_2 = 1.35$ using the same method but a pre-Hipparcos parallax of 31 mas. Our results, altough close to theirs, is more reliable. The radius of the primary, estimated from the Hipparcos parallax and from $T_{\rm eff} = 7750$ K (Faraggiana & Gerbaldi 1993), is $R = 3.03 \pm 0.25\ R_\odot$, which implies an equatorial velocity $v_{eq} = 8.3 \pm 0.7\ \mathrm{km\,s^{-1}}$. If the rotational equator of the star coincides with the orbital plane, then the projected rotational velocity is $v \sin i = 7.7 \pm 0.7\ \mathrm{km\,s^{-1}}$, in excellent agreement with the value (which may be overestimated, however) listed in Table 2. In these estimates, we assumed a negligible interstellar absorption and adopted the difference $\Delta V = 1.7$ mag between the components of this speckle binary (Tokovinin 1985), so that the apparent visual magnitude of the primary component alone is 3.876 instead of 3.670 for the whole system (Rufener 1988).

The HR diagram is shown on Figure 6. Strangely enough, the agreement between the observed location of β

CrB and the evolutionary track at the observed dynamical mass is very poor: both the primary and the secondary (if we rely on $\Delta V = 1.7$) appear overluminous compared to the evolutionary tracks drawn for their mass. Considered alone, the primary might well be at the very tip of the blue hook at the core-hydrogen exhaustion phase, which would reconcile within one σ its observed and theoretical locations in the HR diagram. Its logarithmic age might then be 9.05 dex instead of 8.9. However, the secondary (indicated in Figure 6 as a dot arbitrarily placed along the abcissa on the isochrone $\log t = 8.9$) seems overluminous as well, making the puzzle more complicated but also more interesting, and certainly well worth further investigations. Unfortunately, it is not possible to test completely the position of the secondary because of its unknown colours[2]. Such an information would be most interesting to test the idea of Hack et al. (1997) that the companion might be a λ Boo star with $T_{\rm eff} \sim 8200$ K, although such a hypothesis appears difficult to maintain in view of Figure 6.

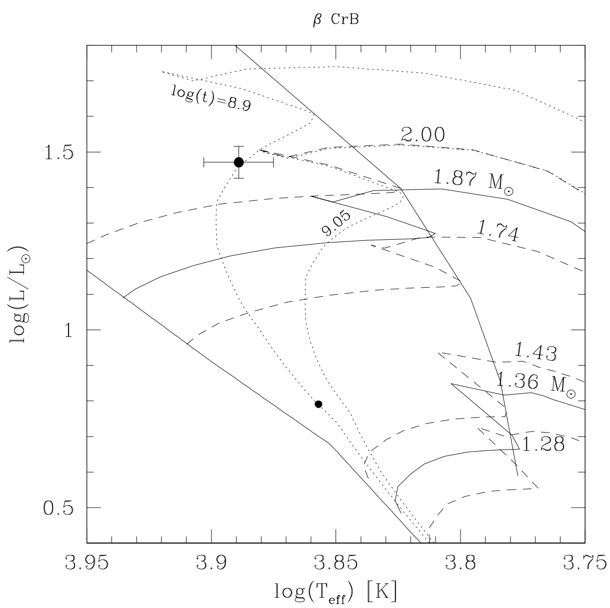

Fig. 6. HR diagram of β CrB. The ZAMS, TAMS and evolutionary tracks interpolated for the observed masses are shown as solid lines, while those interpolated for the masses $\pm 1\ \sigma$ appear as broken lines. The dotted lines indicates the isochrones at $\log t = 8.9$ and 9.05 (t in years).

The semi-major axis of the orbit of the binary's photocenter is given in the Hipparcos and Tycho Catalogues (Perryman et al. 1997). This allows an independant test of the magnitude difference ΔV: assuming the photocenter to be defined by $E_1 x_1 = E_2 x_2$, where E_1 and E_2 are the respective brightnesses of the components in the H_p passband and x_1, x_2 the distances of the components to the photocenter such that $x_1 + x_2 = a_1 + a_2 = a$, one obtains $a_{\rm o} = 1.77 \pm 0.07$ au, on the basis of Tokovinin's $\Delta V = 1.7$ (one has $a_{\rm o} = a_1 - x_1$). This is in rough agreement (within three sigmas) with $a_{\rm o} = 1.97 \pm 0.05$ au given in the Hipparcos catalogue. Our estimate assumes a companion with $T_{\rm eff} = 7200$ K and takes into account the colour equation between Hp and V (Vol. 2, p. 59 of Perryman et al. 1997) which leads to $\Delta Hp = 1.71$. Increasing ΔV by about 0.2 magnitudes would bring perfect agreement. Unfortunately, Tokovinin (1985) do not give any error estimate on ΔV.

[2] Bonneau & Foy (1980) give $\Delta m = 1.5$ at 6500 Å, but the uncertainty seems too large for the inferred $V - m_{6500}$ index to be really useful

4. Results on Am stars

4.1. HD 43478 (= BD +32° 1246 = Renson 11540)

This star was classified A3-F2-F5 by Osawa (1965) and Ap Si Sr by Bertaud & Floquet (1974). As kindly pointed by Renson (1994, personal communication to PN), Babcock (1958) had already found it double-lined, but did not give any period. Interestingly, Babcock listed this star as probably magnetic, and mentioned the profile of the K line as peculiar; as Babel (1994) showed, cool magnetic Ap stars have a peculiar profile of the Ca II K line which betrays a stratification of calcium in the star's atmosphere. Perhaps this star should be indeed classified Ap after all. We secured 56 points (see Table 9, 10 and Fig. 7) and obtained the orbital elements listed in Table 1.

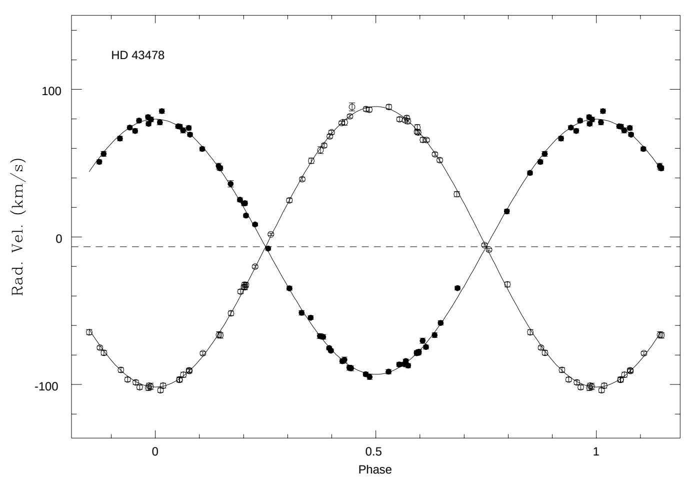

Fig. 7. Radial-velocity curve of HD 43478. The period is 5.464086 ± 0.000011 days. Notice that the zero phase corresponds here to the quadrature (epoch given in Table 1) but not to the primary eclipse (Equation 3) which would fall here at phase 0.75, when the *more massive* component passes *in front* of the less massive one.

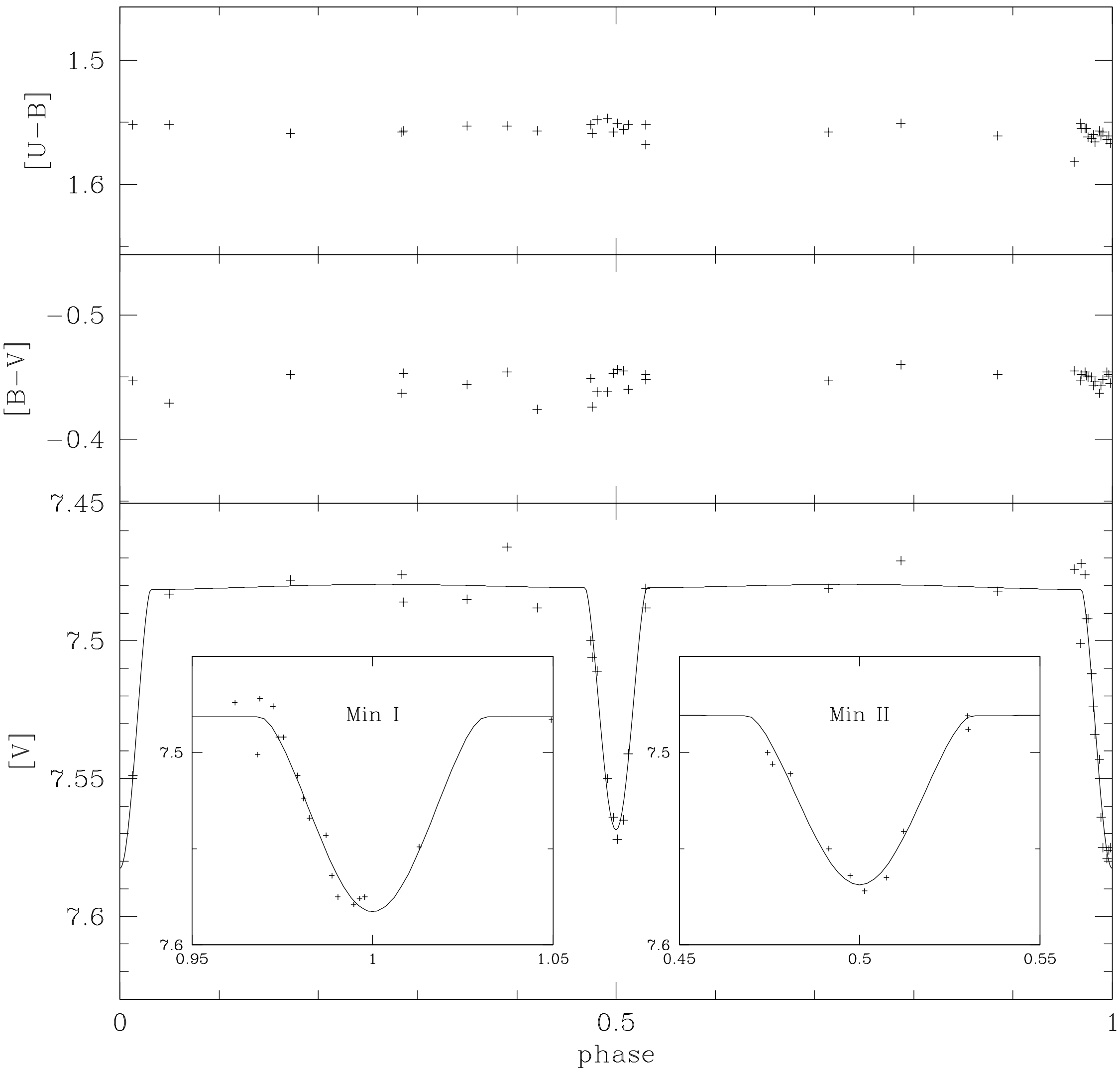

Fig. 8. Lightcurves of HD 43478 for the $[V]$ magnitude and the $[U-B]$ and $[B-V]$ colour indices of Geneva photometry, plotted according to the ephemeris given in Equation 3. Notice the lack of colour change during eclipses. The best fit to the $[V]$ curve is shown (see Table 4).

The system is especially interesting, because we discovered eclipses, which allow to determine the orbital inclination (North & Nicolet 1994). Unfortunately, the eclipses are shallow, as shown if Figure 8 where the lightcurve is plotted according to the ephemeris:

$$HJD(MinI) = 2\,446\,774.790 \underset{\pm 0.003}{} + 5.464086\,E \quad (3)$$

In addition, the number of measurements is small, due to the unfavourable period (close to 5.5 days) and we had a relatively small number of good nights at the Jungfraujoch station on the critical dates. The descending branch of the primary minimum was observed during a mediocre, partial night where only five standards could be measured; nevertheless, the scatter around the fitted lightcurve is fairly good. The two minima have about the same depth and are separated by exactly 0.5 in phase, confirming the circularity of the orbit. On the other hand, the $[U-B]$ and $[B-V]$ curves remain flat during both eclipses, showing that both components have similar effective temperatures. In spite of the small number of points, we analized the lightcurve with the EBOP16 programme (Etzel 1980, 1991). The Geneva and $uvby\beta$ photometric indices and parameters give very consistent $T_{\rm eff}$ and $\log g$ values through the calibration of Künzli et al. (1997) for the Geneva system, and through the calibration of Moon &

Dworetsky (1985) for the $uvby\beta$ system (Table 3). For the $uvby\beta$ system, we applied the correction recommended by Dworetsky & Moon (1986) to the $\log g$ value for the Am stars.

From the values of $T_{\rm eff}$ and $\log g$, we interpolated the linear limb-darkening coefficient u from the tables of Van Hamme (1993). With the available photometric data, it is impossible to fit simultaneously all the interesting parameters, namely the central surface brightness of the secondary J_s, the radius r_p of the primary, the ratio k of the radii and the orbital inclination i. This is a well-known difficulty for all systems (even well detached ones) where both components are nearly identical, even when the eclipses are deep. Another type of data has to be used to constrain the ratio of radii, because the latter may be changed from e.g. 0.6 to 1.4, without any change in the *rms* scatter of the residuals. We do not have detailed spectroscopic informations, but the CORAVEL data allow to have a rough guess of the k ratio in the two following ways:

1. The width (FWHM) of the autocorrelation dip can be translated in terms of $v \sin i$ through a proper calibration (Benz & Mayor 1984). Assuming there is no other cause of broadening than in normal stars (i.e. no Zeeman broadening, for instance), one obtains in this way the projected rotational velocities given in Table 2. If synchronism has taken place between spin and orbital periods, which appears highly probable given the rather evolved state of the system (low $\log g$) and the circular orbit (circularisation time is longer than synchronisation time according to tidal theories), then k is directly given by the ratio of the $v \sin i$ values, i.e. 0.73.
2. The equivalent width W of the autocorrelation dip depends on effective temperature and metallicity of the star, but also on the amount of dilution of the stellar flux by the companion's flux. Assuming that both stars have the same effective temperature (as suggested by the flat $[U-B]$ and $[B-V]$ curves) and the same metallicity (a more adventurous assumption), the ratio W_2/W_1 gives directly the luminosity ratio L_2/L_1 and is equal to the square of the ratio of radii k^2. One obtains in this way $k = 0.79$.

A larger weight has to be granted to the first method, so we adopt here $k = 0.75$, keeping in mind that the uncertainty on this quantity remains considerable (20% or so). The final elements found with the EBOP16 programme are given in Table 4. They are rather approximate, but the inclination is relatively well determined and so are the masses too. It is necessary here to comment briefly on the definition of "primary" and "secondary" components, because it is not necessarily the same when radial velocities, respectively lightcurves are considered. From the radial-velocity standpoint, the primary evidently corresponds to the smaller amplitude K and to the more massive component. But, when interpreting the lightcurve, the EBOP code assumes that the deeper (or primary) eclipse corresponds to the *secondary* passing in front of the primary component. In this particular system, it is interesting to notice that the primary minimum corresponds to phase 0.75 of the V_r curve, where the *less* massive component lies *behind* the primary, not the reverse. Therefore, the adopted ratio of radii entered into the EBOP code should not be $k = r_2/r_1 = 0.75$, but $k = r_s/r_p = 1.333$, since we have to identify the dynamical primary (1) with the photometric secondary (s) and the dynamical secondary (2) with the photometric primary (p). Interestingly, this implies a larger surface brightness of the dynamical secondary than of the primary, i.e. a slightly larger effective temperature, a relatively rare occurence. The effective temperatures have been computed from an apparent $T_{\rm eff} = 6944$ K (average of Geneva and $uvby\beta$ estimates) which is assumed to result from a weighted average of the components' reciprocal temperatures: $\theta_{\rm eff}(apparent) = 0.7258 = (L_1\theta_1 + L_2\theta_2)/(L_1 + L_2)$, and assuming $J_s/J_p = (T_{\rm effs}/T_{\rm effp})^4$. The bolometric luminosity has been computed assuming $M_{\rm bol\odot} = 4.75$.

Table 4. parameters of HD 43478 obtained from the $[V]$ magnitude using the EBOP16 code and assuming the ratio of radii $r_2/r_1 = 0.75$. The indicated errors are the formal ones only and do not include the large uncertainty on k. Notice that the subscripts p and s refer to the *photometric* primary and secondary respectively (the "secondary" being defined as the foreground star at Min. I) but correspond to the subscripts 1 and 2 (in this order), which correspond to the more and less massive star respectively.

Parameter	value $\pm\sigma$ ([V] band)
i [°]	78.94 $\pm$0.35
$r_p = R_p/a = R_2/a$	0.1157 $\pm$0.0033
$k = r_s/r_p = R_1/R_2 = 1/0.75$	1.333
$r_s = R_s/a = R_1/a$	0.1542 $\pm$0.0044
$u_p = u_2$	0.500
$u_s = u_1$	0.500
$J_s/J_p = J_1/J_2$	0.914 $\pm$0.049
$L_p/(L_p + L_s) = L_2/(L_1 + L_2)$	0.38
$L_s/(L_p + L_s) = L_1/(L_1 + L_2)$	0.62
$\sigma_{\rm res}$ [mag]	0.0073

A summary of the physical parameters of the HD 43478 system is given in Table 5. The bolometric correction has been taken from Schmidt-Kaler (1982). The distance is shorter than indicated by the Hipparcos satellite, which gave $\pi = 3.87 \pm 0.93$ mas or $d = 258^{+82}_{-50}$ pc; however, the discrepancy cannot be considered significant since it remains largely within two sigmas. The distance deduced from the fundamental radii and photometric effective temperatures is almost twice more accurate than that given by Hipparcos (the error has been estimated

Table 3. Physical parameters of HD 43478 according to its colours in the $uvby\beta$ and Geneva photometric systems. Both components are assumed to be identical. Note that $E(B2-V1)=1.146E(b-y)$. The errors quoted for the physical parameters determined with Geneva photometry are propagated from typical errors on the colour indices but do not include possible systematic errors related with the calibration itself. The reddening $E(B2-V1)=0.089$ corresponds to $E(B-V)=0.1$ suggested by the maps of Lucke (1978) and is mentioned only to illustrate its effect on the physical parameteres; the adopted colour excess $E(B2-V1)=0.045$ is obtained from $E(b-y)=0.039$, which results from the calibrated $uvby\beta$ colours.

Photometry	$T_{\rm eff}[K]$	$\log g[cgs]$	$[M/H]$	$E(b-y)$	$E(B2-V1)$
$uvby\beta$	7026	3.76	0.88	0.039	
Geneva	6862 ± 51	3.78 ± 0.16	0.47 ± 0.06	0.039	0.045
	7189 ± 58	4.18 ± 0.08	0.55 ± 0.07		0.089

Table 5. Physical parameters of the components of HD 43478. The error on the masses includes a large, 20% uncertainty on k, which translates into a $\pm 0.27^{\rm o}$ uncertainty on i. The same is true of the radii, whose uncertainties are mutually anticorrelated since the sum of radii remains constant within 3% as k is varied.

	Primary	Secondary
$\mathcal{M}/\mathcal{M}_\odot$	1.880 ± 0.018	1.710 ± 0.017
$R/R_\odot$	3.08 ± 0.24	2.31 ± 0.31
$\log g$ [cgs]	3.735 ± 0.072	3.94 ± 0.12
$v \sin i$ [km s^{-1}]	28.1 ± 2.8	20.6 ± 2.1
$\log T_{\rm eff}$ [K]	3.838 ± 0.010	3.847 ± 0.010
$\log L/L_\odot$	1.28 ± 0.11	1.07 ± 0.16
M_{bol}	1.55 ± 0.27	2.08 ± 0.39
$B.C.$	-0.10	-0.10
M_v	1.65 ± 0.27	2.18 ± 0.39
$E(B2-V1)$	0.045 ± 0.015	
A_V	0.17 ± 0.06	
Distance [pc]	172 ± 22	
Age ($\log t$, t in years)	9.10 ± 0.08	

using the usual propagation formula applied to the distance modulus). It is interesting that the fundamental $\log g$ value we find for the primary, which is quite reliable, is in excellent agreement with the value obtained from both Geneva and $uvby\beta$ colour indices.

The situation of both components in the HR diagram is shown in Figure 9, together with $Z=0.020$ evolutionary tracks interpolated in those of Schaller et al. (1992) and isochrones with ages $\log t=9.1$ and 9.2. The primary is clearly at the end of its life on the Main Sequence, and the secondary is probably somewhat evolved too. In view of the shape of the isochrones, one can easily understand why the secondary is slightly hotter than the primary. Clearly, a more complete and precise lightcurve is needed, especially to give a more accurate, fundamental estimate of the radii and to assess thereby the validity of the assumption of synchronism.

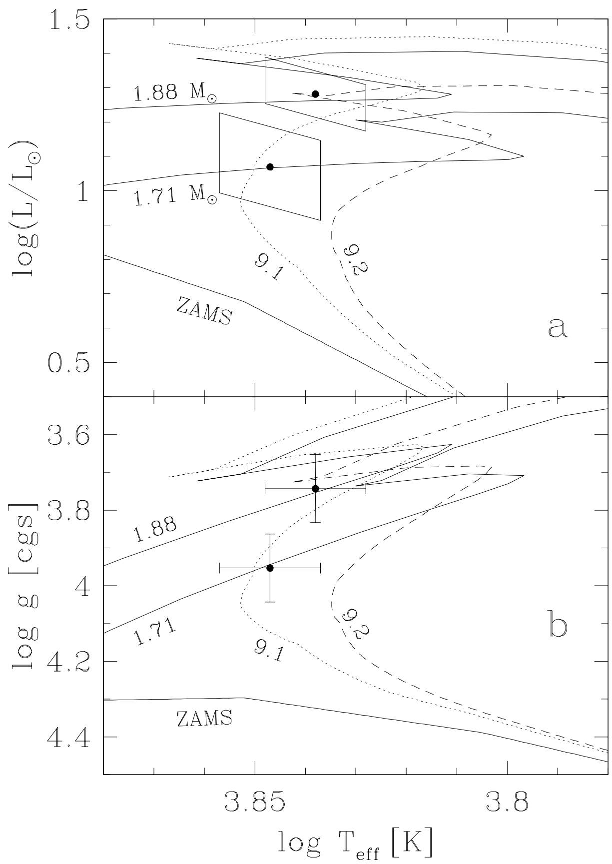

Fig. 9. HR and $\log g$ vs $\log(T_{\rm eff})$ diagrams for both components of HD 43478. The position of the primary is fairly well defined, while that of the secondary is less reliable. The continuous lines are the ZAMS and evolutionary tracks interpolated for the measured masses, while the dotted and broken lines are the isochrones at $\log t=9.1$ and $\log t=9.2$ respectively.

4.2. HD 96391 (= BD +72° 515 = Renson 27770)

This star was classified A4-F0-F3 by Abt (1984). It is also an SB2 system with very similar companions. Unfortunately, we do not have Geneva photometry for that star, but Strömgren photometry[3] done by Olsen (1983) and re-

[3] b-y = 0.220, m_1 = 0.225, c_1 = 0.656, V = 7.08

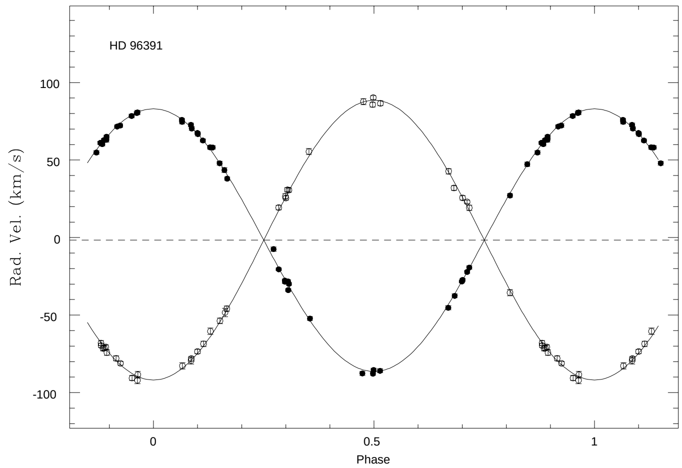

Fig. 10. Radial-velocity curve of HD 96391. The period is 4.915427 ± 0.000008 days.

trieved using the General Catalogue of Photometric Data (Mermilliod et al. 1997) gives $T_{\rm eff} = 7020\ K$, $\log g = 3.85$ through the calibration of Moon & Dworetsky (1985), and $\Delta m_0 = -0.051$, $R/R_\odot = 1.74$, $M_V = 2.66$, $M_{bol} = 2.59$ and $\log(L/L_\odot) = 0.82$ through older calibrations included in Moon's (1985) code. We have 36 CORAVEL observations of this star (Tables 11 and 12); the orbital elements are listed in Table 1 and the $v \sin i$ value of each component is given in Table 2. The i angle remains unknown, since that star is not known as an eclipsing binary.

On the other hand, the Hipparcos parallax is $\pi = 6.81 \pm 0.62$ mas, which implies a distance $d = 152$ pc taking into account the Lutz-Kelker correction -0.07. Furthermore, from the reddening maps of Lucke (1978), a colour excess $E(B-V) = 0.029$ appears reasonable, so we adopt $A_V \sim 0.10$; to correct for the duplicity, the apparent visual magnitude is increased by 0.75 mag (so the result will relate to an average component), and one obtains $M_V = 1.82$, $\log(L/L_\odot) = 1.198 \pm 0.089$, and by interpolation in theoretical evolutionary tracks, $\log g = 3.84 \pm 0.08$ dex, $\mathcal{M} = 1.819 \pm 0.070 \mathcal{M}_\odot$ and $R = 2.69 \pm 0.30 R_\odot$. The agreement of the $\log g$ value obtained here with that given by the *uvby* photometry is excellent (the photometric luminosity is far off, but is obtained through an older calibration). Once again, this system appears close to the end of its life on the main sequence. It is now possible to estimate the orbital inclination i by comparing $\mathcal{M} \sin^3 i \simeq 1.38 \mathcal{M}_\odot$ with $\mathcal{M} = 1.82 \mathcal{M}_\odot$ and the result is $i \simeq 66°$. This precludes eclipses, which would need an orbital inclination larger than $\sim 73°$ to occur. The individual masses are about $\mathcal{M}_1 = 1.85 \mathcal{M}_\odot$ and $\mathcal{M}_2 = 1.73 \mathcal{M}_\odot$. The average equatorial velocity computed from the radius obtained above and from the assumption of synchronism is 27.7 $\mathrm{km\,s^{-1}}$, which translates into $v \sin i \simeq 25$ $\mathrm{km\,s^{-1}}$. This value may be compared with the observed $v \sin i$'s of both companions (Table 2), if the spin axes are perpendicular to the orbital plane: the observed values are smaller than those predicted by synchronism via the radius estimate, but the 11% error on the latter is large enough to accomodate both results within two σ. The system is very probably synchronised.

5. Conclusion

We have shown that the cool Ap star HD 8441 belongs to a triple system, whose ratio of the long to the short period is larger than 47.

We could improve the knowledge of the orbit of the classical Ap star β CrB thanks to our new, highly homogeneous radial velocities which could be combined with the published speckle orbit. Furthermore, the individual masses of the components could be determined thanks to the Hipparcos parallax.

The masses of both components of the Am star HD 43478 could be obtained with 1% accuracy thanks to the eclipsing nature of the system. The radii are less precisely known, because of the shallowness of the eclipses and the insufficient photometric data. Nevertheless, the assumption of synchronism combined with the present data leads to a very good match of both components with the isochrone $\log t = 9.1$, and the evolved state of at least the primary clearly appears even without this assumption. It would be worthwhile to make further photometric observations of this system, in order to obtain a better estimate of the radii and to tell whether it is synchronized or not. Spectroscopic observations should also be done in order to constrain the luminosity ratio and the individual effective temperatures.

Finally, we obtained a good mass ratio for the Am star HD 96391 and could also estimate its orbital inclination from an independant mass determination using the Hipparcos parallax.

All four binaries examined here have at least one component (the primary) which is significantly evolved and will leave the Main Sequence within a short time, relatively to its MS lifetime. The rotational period of both components is very probably synchronised with the orbital period in the two systems hosting Am stars.

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